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# THE GEOLOGY OF CENTRAL MINAS GERAES, BRAZIL

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### INTRODUCTION

The South American continent bears resemblance to the North American continent in several respects. Like the northern continent it may be divided according to its geologic history into an eastern half and a western half. Like North America its Atlantic side was deformed and thrown into mountains before the close of the Paleozoic. As in our own Appalachians this mountain-building period of eastern South America was followed by long-continued erosion which base-leveled the mountains. Later successive widespread uplifts produced low plateaus, out of which rejuvenated erosion has carved the present ranges. Aside from these gentle uplifts, which have occurred at several periods during later geologic history, the eastern part of the continent has exhibited comparative stability for a long time. Since the Paleozoic the deformation of South America has largely been on the Pacific side. During the Mesozoic and Tertiary remarkable stressed conditions on the Pacific border developed the great world-ridge of Cordilleras which runs from Cape Horn to Bering Strait and which makes the western portions of the two continents also geologically related.

The area considered in the present paper lies in the eastern half of the South American continent. It is that section of the state of Minas Geraes, Brazil, which lies between Diamantina (latitude 18°17′ S.) and Ouro Preto, the former capital of the state (latitude 20°23′ S.), which is situated east of the 45th meridian. In many respects this area is geologically the most typical and complex part of eastern Brazil. Running north and south across it is the Serra do Espinhaço, or Backbone Ridge of Brazil, which forms the eastern rim of the São Francisco basin and divides the waters flowing into the Rio São Francisco from those which flow directly into the Atlantic Ocean. Structurally and historically this mountain range gives the key to the geology of most of eastern Brazil, for either within the range, or closely associated with it, are all the important sedimentary formations of Minas Geraes. These comprise a great series of quartzites, schists, and iron formations with some associated limestones. East of the Serra do Espinhaço is a great area of dominantly igneous rocks, presumably Archean, which extends, with the exception of small isolated patches of overlying sedimentary rock, continuously to the sea. West of the Serra do Espinhaço is a plateau country underlain by rocks of both the sedimentary series and the basement complex.

Within this region structurally so significant, occur also the most important mineral deposits in Brazil (Fig. 1). Here is found the gold which caused this portion of the country to be settled at an early date. Here also are found the diamonds and other precious stones for which Brazil has long been famous. And it is along the flanks of this strip of the Serra do Espinhaço that there are being discovered today the still more remarkable deposits of high-grade iron ore which seem destined to develop a great industry in the future.

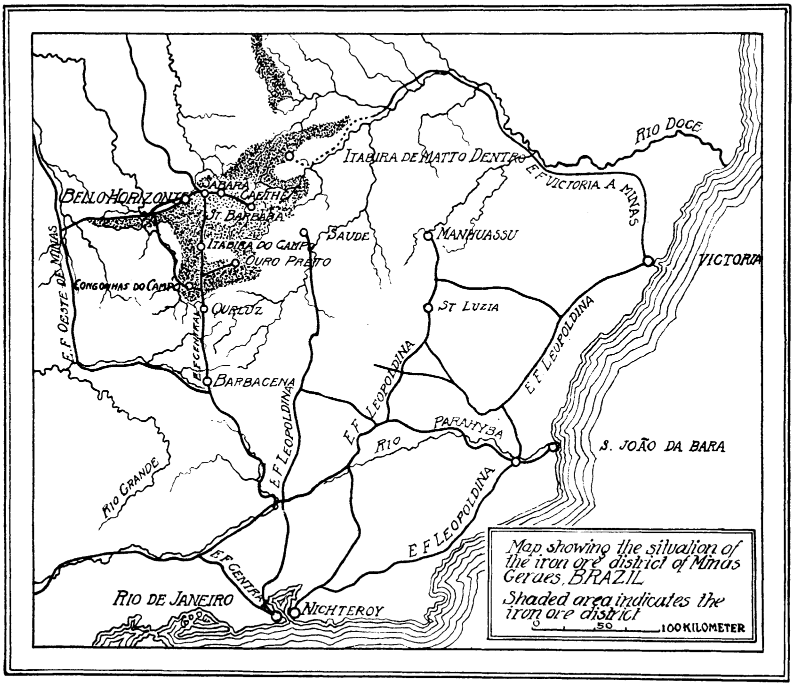

FIG. 1.—Map showing the location of the iron-ore district of Minas Geraes, Brazil

## GENERAL GEOLOGY

### GENERAL DISTRIBUTION, SUCCESSION, AND STRUCTURE OF FORMATIONS

The coastal region of Brazil throughout the states of Rio de Janeiro and Espirito Santo is composed, except for small areas of Mesozoic or Tertiary sediments occurring locally along the ocean border, of a complex of ancient crystalline rocks of which granite, gneiss, and crystalline schist are the prevailing types, and in which diorite, gabbro, and other more basic rocks occur as intrusives. These rocks form the basement complex of eastern Brazil and are probably to be referred to the Archean. The crystalline belt extends far into the interior, at first continuously, but farther away from the coast, as patches and arms amid areas of overlying post-Archean sedimentary formations.

Eastern Brazil has been, throughout much of its geologic history, a region more subject to denudation than to sedimentation. In Minas Geraes the uncovered basement complex is now areally the most extensive surface formation. The basal granite, gneiss, and crystalline schist are nearly continuous throughout the eastern and central portions of the state. Where the younger sedimentary beds do occur, they persist in favored localities as local remnants of former widespread formations. The post-Archean sedimentary series is best represented within the limits of the Serra do Espinhaco which owes its existence and present elevation to the superior resistance of some of its quartzite beds.

The area of post-Archean sedimentary rocks of central Minas Geraes extends in a continuous belt of varying width from about latitude 20°40′ S., in south-central Minas Geraes, northwestward across the state and into the state of Bahia. Southward from latitude 20°40′ S. isolated areas of sediments continue into southern Minas. As a result of complex earth movements, the southern end of the principal sedimentary belt is wide and irregular, occupying nearly all of the area from a point about 15 kilometers southeast of Ouro Preto, northwestward to Bello Horizonte, a width of about 80 kilometers. Followed northeastward the belt narrows but continues as a strip from 5 to 20 kilometers in width almost to Diamantina, where it branches, one limb running northeastward into northeastern Minas Geraes and the other continuing northward into Bahia. Both on the east and west, this strip of sediments is bounded by extensive areas of older rocks, probably Archean, consisting of gneiss, granite, and crystalline schists. Areas of sediments, of unknown age, however, occur at various places west of the sedimentary belt, becoming more extensive toward the north.

The metamorphosed sediments, which Derby has called the Minas series,[1] are probably of Algonkian age, judging from their stratigraphic position and lithology and their similarity to Algonkian sediments in other places. They lie upon the eroded surface of the basement complex, and have as their basal member a great quartzite formation. Above this quartzite, often separated from it by a thin argillaceous schist bed, is the peculiar iron-bearing quartzite known as itabirite, accompanying which are extensive iron-ore lenses. This formation is, in turn, overlain by a schist and quartzite formation of great thickness. The uppermost known member of the great series is a quartzite with associated schists. Occurring in proximity to these metamorphosed sediments, and derived from them by disintegration and decomposition, are subaerial deposits of more recent age.

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[1] O. A. Derby, "The Serra do Espinhaço, Brazil," *Jour Geol.*, XIV (1906), 396.

Appropriate geological names taken from localities where characteristic exposures of the various formations occur have been adopted. The known succession is as follows:

- Tertiary and Quaternary
  - River gravels
  - Tertiary clay and lignite
  - Canga deposits
- Mesozoic or Early Tertiary
  - Diamantina conglomerate
- Probable Algonkian
  - Itacolumi quartzite
  - Piracicaba schist and quartzite
  - Itabira iron formation
  - Batatal schist
  - Caraça quartzite
- Probable Archean
  - Gneiss, granite, and schist

The various sedimentary formations are complexly distributed, occurring in some places and being absent elsewhere. Their irregularity of occurrence is due, in part, to irregularity in original deposition, but more especially to later faulting and folding followed by very extensive erosion. They are separated from the basement complex by a profound unconformity.

The most characteristic formation of the series is the Caraça quartzite which extends throughout the length and width of the sedimentary area and locally develops an extraordinary thickness.

Somewhat more limited in occurrence is the iron formation which is well developed in the broad portion of the area between Ouro Preto and Bello Horizonte, but which to the northeast and southwest becomes inconspicuous or is entirely absent. The upper formations are also local in their occurrence (Fig. 2).

The Caraça quartzite forms the most prominent mountain system of this portion of Brazil which has taken the name Serra do Espinhaço, or Backbone Range, and which divides the waters flowing westward into Rio São Francisco from those flowing eastward directly into the Atlantic Ocean. The iron formation generally forms well-marked foothills along the quartzite ridges, though locally, where well developed, and specially hard, it itself forms the main ridges while the quartzite is on the slopes. The Piracicaba schist, being soft, is inconspicuous topographically, but the Itacolumi quartzite forms a number of prominent peaks and ridges.

The distribution of formations is well shown by the topography. The mountain peaks and long continuous ridges common to this region are made up of quartzite and iron formation. They are bounded by lower areas of schist, or by an irregular undulating region of hills and valleys underlain by gneiss and granite. These sedimentary rock mountains of central Minas Geraes are, with the exception of the granite masses forming the Itatiaya Range on the southern border of the state and Caparaó Mountain on the boundary between Minas Geraes and Espirito Santo, the most conspicuous mountains in Brazil.

The characteristic deformation of the rocks of central Minas Geraes has been thrust faulting and accompanying folding. The forces in general came from the east and south, ranging between northeast, southeast, and south, forces from different directions being applied at different times, resulting in a sort of superimposition of structure. This complex structure is especially characteristic of the wide area between Ouro Preto and Bello Horizonte, where the combination of forces has resulted in the formation of a number of parallel and intersecting belts of sedimentary rock. In the southern part of this area is an east-west syncline resulting in two parallel belts of sediments; in the western part is a north-south overturned syncline causing a similar distribution, and in the

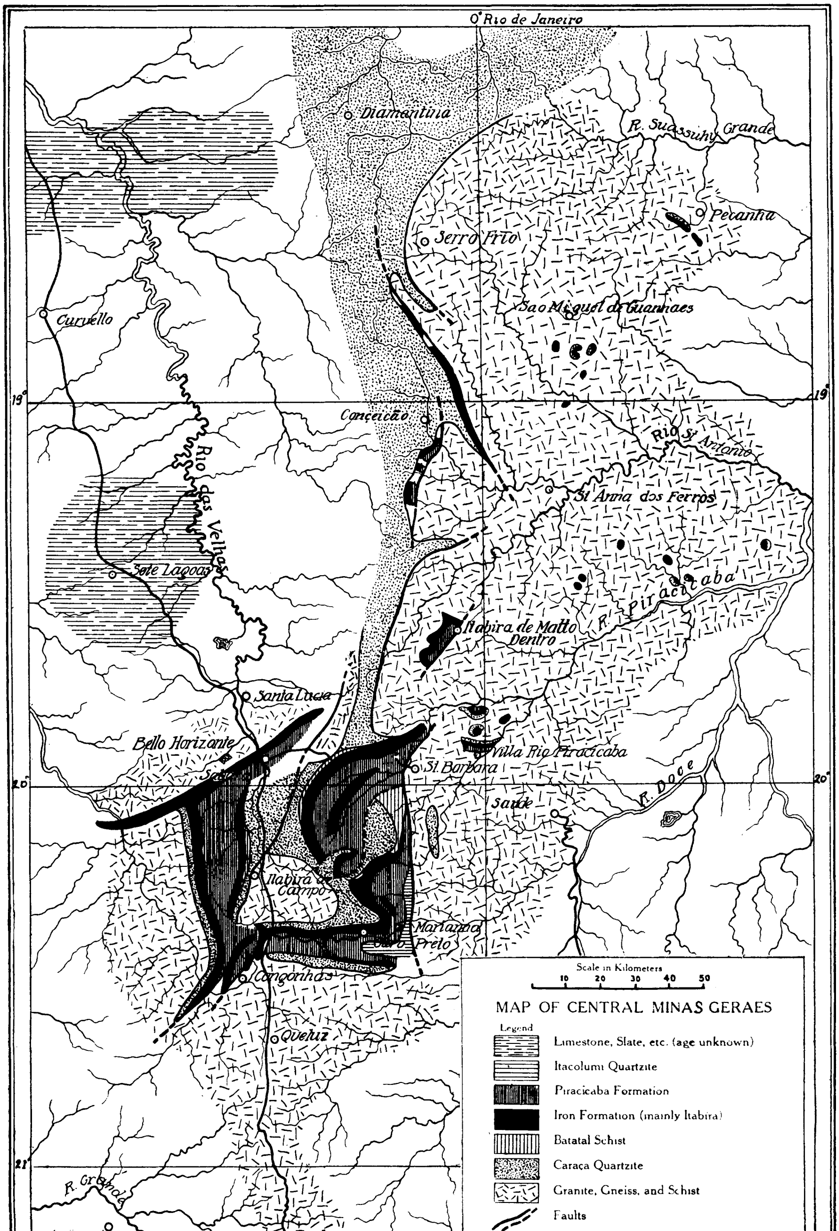

FIG. 2.—Map of central Minas Geraes

northern and eastern parts is a series of more or less parallel thrust faults, resulting in several parallel and branching belts of sediments. In the center, occupying the angle between the two synclines, is a large circular area of granite, gneiss, and schist of the basement complex raised by this combination of forces into a dome structure.

A very conspicuous result of the deformation has been the development of V-shaped branchings of the formations in various parts of the area, such as those south of Capanema, west of Cocaes, southwest of Bello Horizonte, and northwest of Serro. These V-shaped junctions can be explained by forces working in different directions at the same or at different times, in such manner that, when breaks occur in the formation, one portion of it is forced against another portion at an angle. Frequently at such junctions there has been much crushing and dislocation of the formations.

In general the irregularity of deposition, resulting in a great variation ot thickness as well as of materials, combined with the complex structural relations above mentioned, has resulted in a condition of complexity of structure and areal distribution of formations not easy to solve.

## PROBABLE ARCHEAN

*Basement complex.*—The rocks of the basement complex consist chiefly of granite of varying composition and texture, gneiss with interlayered amphibolite, and micaceous and quartzose schists. Granite and gneiss are probably the most abundant of the rocks in the Archean areas, and of these two the granite is the more commonly observed because of its greater hardness. It forms prominent ridges in many parts of central Minas, and is commonly exposed in rounded bluffs along streams where these flow through granite areas. Crystalline schists are also abundant but are less conspicuous because, on account of the softness of these rocks, exposures are not so common. These schists resemble closely the schist beds in the Piracicaba formation and sometimes can be distinguished from them only by their general distribution. Elsewhere they may be distinguished by their more prominent recrystallization, or by the presence of pegmatite veins. Such pegmatite veins are also abundant in the gneiss but are rarely seen in the granite. They usually consist of muscovite, orthoclase, and quartz.

The amphibolite is a banded rock occurring interlayered in the gneiss and corresponding in layering to the gneiss itself. It is a dark-green rock consisting either entirely of hornblende, or of hornblende with a small amount of feldspar. It is widely distributed throughout the region of the basement complex, and in many localities masses of considerable thickness occupy large areas. On weathering the amphibolite gives rise to a yellow ocherous soil due to the formation of abundant iron oxide. Near the surface this changes in color to a deep red which is very characteristic of the soils in many parts of the district.

Diorite and gabbro occur sparingly as later intrusions in the gneiss and schist in different parts of the district, diorite being more common than gabbro. Most of the intrusions are in the form of dikes, some of which may be traced for long distances. Some of the gabbro intrusions, however, are very limited in extent.

The relation of the three principal varieties of rock in the basement complex to each other is determined with difficulty on account of the complexity of their structure and distribution, and because of the thick covering of mantle rock which effectively conceals the greater portion of these rocks. The granite is apparently intrusive into the gneiss and schist and occurs in large irregular areas. Single masses 60 or 70 kilometers in extent are known. The granite intrusions are probably older than the gabbro and diorite. The relation between the schist and gneiss is unknown. In places the schist has been seen interlayered with the gneiss and apparently bears a relation to it similar to that which the amphibolite bears to the gneiss. If this is true the schist, gneiss, and amphibolite would seem to be the older rocks into which granite, diorite, and gabbro were intruded. Probably the gneiss and amphibolite represent respectively ancient acid and basic volcanic flows with which were interbedded quartzose and argillaceous sediments now represented by the schists. By metamorphism and deformation these were transformed into their present equivalents—

the igneous rocks to gneiss and amphibolites, the sediments to crystalline schists. The later intrusions may have taken place during, or after, the deformation.

Many areas of schist, the definite structural relations of which it has not been possible to determine, have been presumed to be part of the basement complex. During further investigations certain of these schists may be found to belong to one, or other, of the overlying sedimentary formations.

Lithologically the schists of the basement complex are extremely various. There are quartz-muscovite schists, sericite schists, talc schists, chlorite schists, amphibole schists, and argillaceous mica schists of varying texture, many of them ferruginous, others siliceous. The gneiss, on the other hand, is fairly regular in texture and composition throughout most of the district. In most localities it is medium grained with distinct banding, though elsewhere the banding is so faintly developed that it is difficult, by lithology alone, to distinguish the gneiss from later granitic intrusives. Its predominant minerals are feldspar, quartz, biotite, and hornblende.

From the foregoing descriptions it is clear that to distinguish between the various rocks of the basement complex, to separate them areally and determine their structure and relations to each other, will require much petrographic study and detailed mapping.

### POST-ARCHEAN EROSION PERIOD

During the deformation and metamorphism of the gneiss, schist, and amphibolite, and their intrusion by the granite and other igneous rocks, the surface of the central Minas Geraes region was probably of a very rugged and mountainous character, and was probably elevated far above the surface of the sea. Then a period of erosion and disintegration began, for a long time the former being predominant, but later as the mountains were being worn down and acquired gentler slopes disintegration became more and more important. For a long time the products of disintegration and decomposition were largely carried away to the sea, but gradually, as the slopes became more gentle, material began to accumulate and a layer or blanket of soil formed over the solid rock. This thickened as erosion and transportation decreased and as it thickened it became more and more thoroughly decomposed.

While there were still considerable differences of elevation the sea began to encroach upon the land, gradually occupying what is now eastern, southern, and central Minas Geraes. Apparently an arm of the sea extended westward covering the southern end of Goyaz, the southern and western part of Matto Grosso, and probably part of Bolivia. Whether the sea extended far southward into São Paulo is not known, but it is doubtful, since sediments of this age are unknown in central and southern São Paulo. To the north the sea covered northeastern Minas Geraes and a large part of Bahia, but whether it extended still farther north is not known.

It was in this sea that the probable Algonkian sediments of central Brazil were deposited. Owing to the great amount of decomposition which the rocks of the basement complex had undergone previous to the encroachment of the sea, little remained in the soil except the end products, especially kaolin, iron oxide, and silica. As the end products were derived largely from acidic granites and gneisses, silica dominated. In the shallow advancing sea the waves may be supposed to have been capable of sifting these residual materials, holding in suspension and carrying away the fine mud and iron oxide while of necessity soon depositing the coarser grains of quartz. The first material laid down upon the eroded surface of the Archean complex in the area under discussion was therefore a great mass of quartz sand. By cementation, induration, and metamorphism this has become the Caraça quartzite formation.

## PROBABLE ALGONKIAN

*Caraça quartzite.*—The Caraça quartzite is the basal formation of the thick sedimentary series of supposed Algonkian age. Over most of the region the formation consists of more or less schistose quartzite, though it embraces a complete range from pure vitreous quartzite to quartzite schist made up almost entirely of white mica. The variations in composition and texture occur along the beds, as well as across them, so that at different places along the quartzite belts the major part of the formation may be either predominantly schistose or predominantly quartzitic. Locally the formation may be thin-bedded, while elsewhere masses many meters in thickness and of great uniformity in texture may occur without a trace of bedding.

The distribution and structure of the quartzite are determined by the general structure of the district (Fig. 3). The dips are in general to the east or southeast at varying angles, except for minor irregularities such as occur in the region between Ouro Preto and Congonhas do Campo. Even where three or four parallel or slightly intersecting belts of quartzite occur, this regularity of dip prevails. Such parallel belts of southeasterly dipping strata are the results of thrust faulting and overturn folding, and their regularity indicates the uniform nature of the deformation to which the region has been subjected.

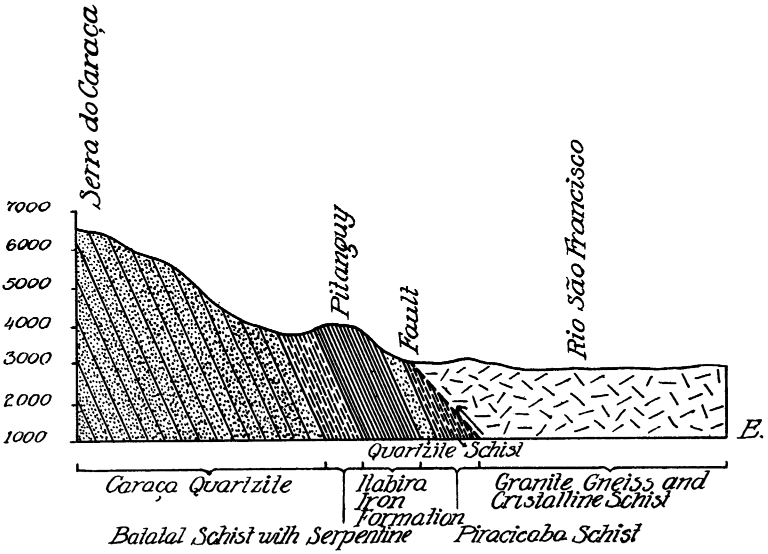

FIG. 3.—East front of the Serra do Caraça. Section through Pitanguy Hill. Elevations given in feet.

The Caraça quartzite though varying in thickness extends throughout the length of the sedimentary belt, being everywhere well developed except in the region east and south of Bello Horizonte where it appears to be absent, for the iron formation lies directly on the basement complex. Along considerable portions of the belt, especially in the northern part, it is the only one of the Algonkian formations present, being bounded on both the east and the west by rocks of the basement complex. In detail the distribution of the Caraça quartzite is as follows: Beginning at the southwest, a belt of quartzite dipping to the southeast runs northeastward to a point about northwest of Congonhas do Campo where it turns northward and continues with great uniformity to about the latitude of Bello Horizonte where it is cut off sharply by a northeast-southwest belt of sediments. To the east of it, and approximately parallel with it, is a shorter quartzite belt also dipping to the east. Between the two belts are areas of iron formation and Piracicaba schist, while to the east and west of them are granite, gneiss, and schist of the basement complex. From the structure it is presumed that these two north- and south-striking quartzite belts are on opposite limbs of an overturned syncline dipping to the east. Both belts are well shown in the topography, the western one appearing as the Serra da Boa Morte and the eastern one forming the high hills west of Itabira do Campo.

Beginning with Serra do Ouro Branco near Miguel Burnier is an east-west belt of quartzite somewhat more irregular than are the north-south belts, being broken at several places, and varying in strike in different parts, from northwest-southeast to northeast-southwest. It continues eastward to a point southeast of Ouro Preto where it is cut off by rocks of the basement complex. South of it, unconformably underlying it, are schist, gneiss, and granite of the basement complex. Some distance to the north of it and parallel to it is another quartzite belt dipping southward, being underlain and bounded on the north by granite, gneiss, and schist. Between these two quartzite bands are areas of iron formation and Piracicaba schist, so that here occurs an east-west syncline differing from the north-south syncline before mentioned in being broad and open. The southern limb forms the prominent Serra do Ouro Branco while the northern limb is not very marked topographically, being mainly composed of quartzite schist not very resistant to erosion.

The northern of these quartzite belts continues westward beyond Miguel Burnier and eastward to Ouro Preto where it makes a sharp turn northward and then continues northwestward, thus forming a narrow eastward pitching anticline. The northern limb of the anticline dips to the northeast and rocks of the basement complex are exposed southwest of it along the axis of the anticline. At Capanema the quartzite band branches, one arm going northeastward and forming the conspicuous mountain mass of the Serra do Caraça (Fig. 4) while the other continues northwestward, forming the Serra da Capanema, then, becoming less prominent topographically, it continues northward around the headwaters of the Rio Santa Barbara.

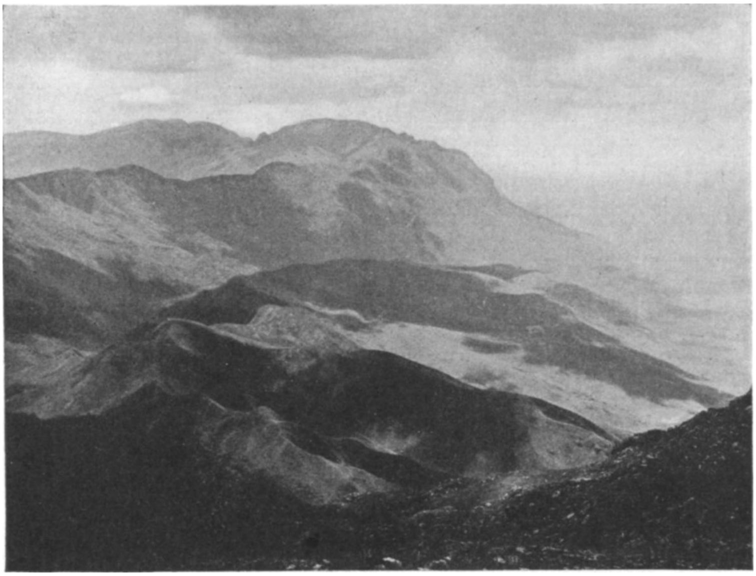

FIG. 4.—The Serra do Caraça at Alegria. A portion of the Backbone Range. The high Serra consists of resistant Caraça quartzite. In the middle distance are hills of the Itabira iron formation whose strata dipping toward the right reach a maximum thickness of 1,200 meters in this section. In the far distance to the right are lowlands of the granite complex.

At a point west of Cocaes the latter belt divides again, an eastern arm forming the prominent ridge above Cocaes and then disappearing, while the main belt here forms the central axis of the Serra do Espinhaço, which continues northward for many miles—a great quartzite range.

Several minor offshoots to the east occur from the northward extension of the range, and at a point west of Serro the range divides, one branch running northeastward, forming the Serra do Chifre, on the divide between Rio Doce and Rio Jequitinhonha, and the other continuing northward past Diamantina toward the state of Bahia.

The northeast-southwest belt of sediments previously mentioned as cutting off the north-south overturned syncline near Bello Horizonte consists mainly of Itabira iron formation and Piracicaba schist dipping southeast. Locally a thin layer of argillaceous and quartzitic schist, representing the Caraça quartzite, occurs at the base. The belt is of considerable extent, beginning at a point northeast of Caethé, east of the main Serra do Espinhaço, and running first southwestward past Bello Horizonte and the end of the north-south overturned syncline already mentioned, and then westward and northwestward toward Pitanguy. It forms a prominent range known as the Serra da Piedade which consists for the most part of iron formation. Toward the west, however, the quartzite becomes more prominent, forming some conspicuous mountains.

The Caraça quartzite, while present almost throughout the district, varies greatly in thickness. In the isolated sedimentary areas in the eastern part of the district, as near Villa Rio Piracicaba, there are places where it is less than 30 meters thick; in the region south and east of Bello Horizonte it appears to be in places entirely absent, while along the main Serra do Espinhaço it reaches thicknesses greater than 1,500 or 1,800 meters. The latter is the more typical development of this great formation.

The ordinary phase of the Caraça quartzite consists of quartz grains intermixed with more or less white mica. Where highly metamorphosed, and this is especially true where the formation is thin, the mica is sometimes coarsely crystalline so that individual flakes frequently reach half an inch in diameter. When quartz occurs in these phases it is also coarsely crystalline. Such coarsely crystalline phases, however, are rare. Where the formation consists largely of quartzite, it is prominent topographically, but where the schist layers are abundant and well developed, it gives way rapidly to erosion.

Both the quartzite and the schist phases are light colored, the quartzite being white, light green, or light brown according to the stage of oxidation or decomposition of its constituents. The light-brown color is due to the oxidation of ferrous iron present and is prevalent near the surface. The schists are usually white, light green, or light gray in color owing to the principal constituent, white mica.

*Batatal schist.*—After the deposition of a great thickness of the coarse clastic sediment which makes up the Caraça quartzite, there came a change in the character of the material being washed into the sea. The sediments became finer, whether owing to the lowering of the land surface from which the material was derived, or to a further advance of the sea upon the land. Whatever the cause, there occurred a slackening of sedimentation as well as progressive fineness. The result was the laying down of a series of varicolored clays which through metamorphism have resulted in the Batatal formation, a light-gray to dark-red, fine-grained, argillaceous schist, which overlies the Caraça quartzite conformably. This schist is perhaps best represented along the base of the Serra do Caraça, though, on account of its softness, it is seldom exposed in outcrop. Not only inconspicuous in outcrop, it is also a comparatively thin formation, seldom exceeding 30 meters in thickness. At one point, however, along the base of the Serra do Caraça northwest of the village of Cattas Altas, it suddenly thickens to more than 300 meters of schist, while at the same time the overlying iron formation gradually pinches out. The situation is somewhat peculiar and it is probable that the upper portion of the Caraça quartzite at that point is schistose, and thus is indistinguishable from the Batatal schist.

On the eastern and southeastern flank of the Serra do Caraça a sheet of serpentinized eruptive rock is found to rest upon the Batatal schist at a number of points. It is seen at Morro da Mina, and is also conspicuous in Boa Vista, near Cattas Altas, extending several kilometers northward from there till cut off by a fault. This serpentine layer always occurs at the same horizon at the top of the Batatal schist and at the base of the iron formation. It is not an intrusive, but was apparently a sheet of basic lava spread out upon the then level surface of the Batatal sediments. The iron oxide and silica deposits which now constitute the Itabira iron formation were then laid in regular succession upon it. If this basic flow were more widely extended throughout the iron district and were of greater mass, one might be inclined to look to it for a source of the iron now locked up in the great iron formation which followed so closely upon it. Such an explanation has been advanced to explain the origin of much of the iron formation in the Lake Superior region. In their great monograph on the geology of the Lake Superior region, Van Hise and Leith have come to the conclusion that the iron formations there are so intimately associated with basic lavas that the source of the iron in the great ore beds is to be sought in the igneous activity.[1]

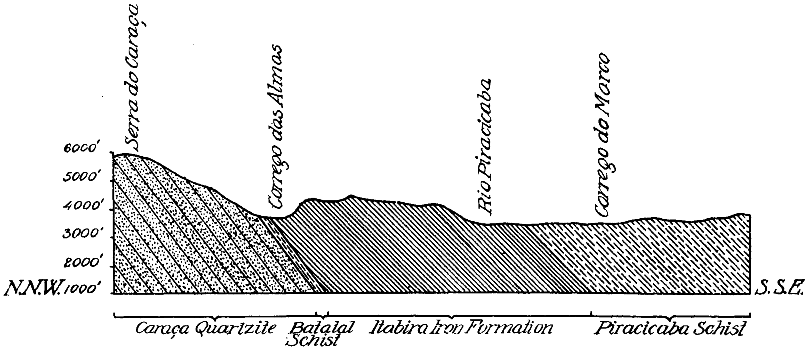

FIG. 5.—Section through Fazenda da Alegria

In Minas Geraes, however, remnants of a basic lava flow near the iron formation in the stratigraphic column have been discovered up to the present time only at the two adjacent localities just mentioned. Though these probably belong to a single flow which extended continuously from Morro da Mina nearly to Santa Barbara, this flow after all covered but a comparatively limited area which, taken together with its thinness, makes it quite insignificant in size and extent in comparison with the tremendous iron formation above it (Fig. 5). Thus it seems more reasonable to account for the deposition of the iron formation through some other agency.

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[1] C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *Mon. 52, U.S. Geol. Surv.* (1911), pp. 409–570.

*Itabira iron formation.*—The Batatal schist represents a slackening of sedimentation from the rapid deposition which characterized the laying down of the sands composing the Caraça quartzite. This slackening of clastic sedimentation continued until the close of the Batatal epoch, when very little clastic material was being washed into the sea in the region considered. The land presumably had become so low as to yield very little mechanical sediment, and with this lowering of the land surface there was probably combined a gradual retreat of the shoreline. Simultaneously with the great diminution in mechanical sediment deposited in the area under consideration, there commenced a precipitation of ferric hydroxide from solution, materials in solution being probably carried beyond the borders of the region of clastic sedimentation. This precipitation may have been due, either to purely chemical reactions taking place in the sea, or perhaps to the operation of the well-known iron bacteria which cause the deposition of ferric hydroxide from waters containing ferrous carbonate in solution. These iron bacteria are said to possess the peculiar property of utilizing as food the carbon dioxide locked up in very dilute solutions of ferrous carbonate.[1] Ferric hydroxide is left behind and is deposited as a sediment. The characteristic reaction may be written: $2FeCO_3+3H_2O+O=2Fe(OH)_3+2CO_2$. This process is operative in very dilute solutions. Apparently only two or three parts of iron per million are needed to make certain types of the iron bacteria active.

Not having much confidence in the hypothesis that the iron oxide was precipitated directly from sea-water by ordinary chemical means, we prefer to turn to the iron bacteria as perhaps forming a better working hypothesis. If such a process as this be supposed to have been steadily in operation at this time, when very little clastic sediment was being deposited, it might have resulted in the production of the extensive iron formation. For reasons which will be discussed later, this hypothesis seems to explain the observed facts connected with the formation of the Itabira iron beds better than any other yet suggested, and to encounter fewer serious difficulties.

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[1] S. Winogradski, "Über Eisenbakterien," *Botan. Zeitung*, Bd. 46 (1888), p. 261; Rudolf Lieske, "Beiträge zur Kenntnis der Physiologie von Spirophyllum ferrugineum Ellis, einem typischen Eisenbakterium," *Jahrb. für wissenschaftlicher Botanik*, Bd. 79 (1911), pp. 91–127.

Like the schist and quartzite, the Itabira iron formation is a true primary sediment.[1] It is a mixture of iron oxide and quartz sand laid down essentially as it occurs today. The principal change which it has undergone since its deposition is the dehydration which has converted the ferric hydroxide originally laid down into ferric oxide, or hematite. This dehydration, like the metamorphism of the shale into Batatal schist and the sandstone into Caraça quartzite, probably is to be associated with the intense deformation which these strata suffered during the mountain-forming movements which antedate the Devonian.

The Itabira iron formation takes its name from Itabira Peak, near the town of Itabira do Campo, a rather striking mountain of splendid specular hematite which forms a conspicuous landmark visible for many miles around. Though varying greatly in character, the Itabira formation is in general hard and resistant and much more durable than the softer schists which lie immediately above and below it. The result is that wherever the iron formation now appears at the surface in inclined beds, it stands up in prominent ridges or as a chain of "iron hills." In some places where both the iron formation and the underlying Batatal schist are very thin, the former may occur simply as a capping, or cover sheet, following the contour of ridges of Caraça quartzite. Elsewhere the iron formation constitutes a separate range of hills in front of, and parallel to, the quartzite ridge. The hills of iron formation are as a rule lower and less massive than those of quartzite, though locally, as along the western rim of the upper Santa Barbara valley, where the quartzite is relatively soft and contains a good proportion of schistose layers, the iron hills overtop the quartzites.

The iron formation varies greatly in thickness. In the ridge running east from Morro Agudo near Villa Rio Piracicaba, the whole formation ranges between 5 and 20 meters in thickness. In Morro Agudo Peak it suddenly thickens to 100 meters (Fig. 6). Thirty-odd kilometers away to the southwest, in the locality known as Alegria, on the east slope of the Serra do Caraça, it has a thickness of over 1,200 meters, which is probably its maximum. It is not a case of steady increase, or decrease, in thickness between areas some distance apart, for at the very eastern end of Alegria the iron formation is comparatively thin, and the swelling from a few score up to 1,200 meters is accomplished in the amazingly short distance of about 3,700 meters along the strike (see Fig. 4). This very remarkable thickening of the deposit in such a short distance strongly suggests the conditions of delta deposition. If the layers of iron formation represent the foreset beds laid down, shingle fashion, on a delta front, the great total thickness of the successive layers may be readily understood, and in this way some of the grave difficulties which would otherwise be encountered in the development

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[1] C. K. Leith and E. C. Harder, "The Hematite Ores of Brazil and a Comparison with the Hematite Ores of Lake Superior," *Econ. Geol.*, VI (1911), 670–86; E. C. Harder, "The 'Itabirite' Iron Ores of Brazil," *ibid.*, IX (1914), 101–11.

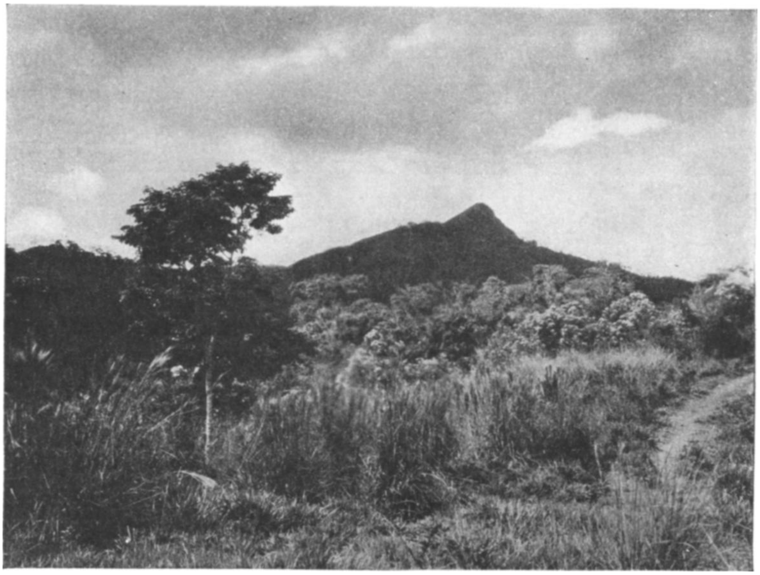

FIG. 6.—Morro Agudo, near Villa Rio Piracicaba. A peak of high-grade iron ore which owes its form to the superior resistance of the hard, specular hematite of which it is composed.

of such a thick deposit are avoided. In the eastern part of the district, as along the Serra da Boa Morte, there seems to be much more uniformity in the thickness of the formation.

In chemical composition the iron formation also varies greatly, and the changes are as sudden as the variations in thickness. In some places, the entire thickness of the formation may be almost pure iron oxide containing less than 1 per cent of impurity. At other points there may have been so much arenaceous material incorporated within the iron sediments that the proportion of metallic iron is reduced to 40 per cent, or even less. But whether the percentage of iron be high or low, the impurities consist largely of rounded grains of quartz sand together with a little phosphorus, the mineralogical relations of which are not known. In places, however, the iron oxide is mixed with clay rather than sand, and beds of ferruginous schist are interlayered with sandy iron formation. Thus, while ferric hydroxide was being precipitated, a certain amount of sandy sediment, and locally, also, clay were washed in to mingle with the precipitate. The presence of impure limestone beds in the lower part of the iron formation, as southeast of Bello Horizonte, shows that carbonate precipitation locally accompanied the iron-oxide precipitation. In some portions of the formation, the sand is more or less evenly disseminated, while in others it occurs more often as distinct sandy partings, or laminae, which separate thin beds of relatively pure iron oxide. The temporary inwash of clastic sediment in the form of sandy partings probably marks unusual storms, or stormy periods, during which more of the terrigenous material found its way beyond the borders of general clastic sedimentation. The rock breaks more readily along the planes of these sandy partings than elsewhere, and hence possesses a somewhat sandy fracture face, so that it appears to contain more sand than is actually the case.

The purer portions of the iron formation, where the proportion of metallic iron exceeds 50 per cent, are regarded as iron ore, while the more sandy portions of the formation are designated itabirite. Formerly the term itabirite was applied as a formation name to the entire iron formation member of the sedimentary series, and included the iron ore as well as the sandy portions and schistose layers. But now its use is being restricted, and the name is applied only in a petrographic sense to the peculiar iron-oxide bearing quartzite which constitutes the sandy portion of the iron formation.[1] There is, however, a complete gradation between the itabirite and the ore.

*Piracicaba formation.*—After a period of very little wash from the land, during which the iron formation was laid down through rapid precipitation chiefly, an epoch of more abundant clastic sedimentation again set in. This change was probably brought about by a gentle uplifting of the land relative to the sea-level. At first only the finer muds were laid down in the region under consideration; later, with changing conditions, there were oscillations both in the direction of diminishing clastic sedimentation and a return to the iron-oxide and calcium-carbonate forming conditions, and also in the direction of increasingly coarse clastic sedimentation with the deposition of what has since become quartzite. Under these fluctuating conditions which followed the deposition of the Itabira iron formation there was laid down a great mass of sediment, in which clays and muds predominated, but within which there were included quite extensive lenses and more or less irregular beds of quartz sand, iron oxide, and also calcium-carbonate deposits. Through subsequent metamorphism these sediments were altered to argillaceous and quartzite schist, quartzite, iron formation, and limestone. The name Piracicaba formation has been given to this series from the Piracicaba River, whose upper course near Santa Rita Durão and in Alegria follows the strike of these beds.

The lenses and beds of limestone and iron formation occur principally in the lower part of the Piracicaba formation, being interlayered with schists, while the quartzite beds predominate in the upper part. Limestone lenses, though usually small, are numerous in many parts of the district, especially in the central and southwestern parts. The limestone is generally impure, containing, besides calcium carbonate, carbonates of magnesium, iron, and manganese. Different lenses differ in composition, some being reddish or purplish in color and containing manganese carbonate as the principal impurity, while others are grayish or brownish and contain iron carbonate as impurity. In places thin layers of itabirite occur in the limestone lenses, or considerable thicknesses of interlayered limestone and itabirite may occur.

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[1] The term itabirite is coming into more general usage as is shown by the fact that it has been applied to iron-oxide bearing quartzites occurring in certain parts of Europe. See F. Beyschlag, J. H. L. Vogt, P. Krusch, *Ore Deposits*, I, 113, 194 (translation by S. J. Truscott).

The iron formation lenses in the Piracicaba formation are generally more extensive than the limestone lenses but are more local in their distribution. In lithology they are similar to the Itabira iron formation, consisting mainly of itabirite but containing also lenses of pure hematite and beds of ferruginous schist. In most cases the iron formation lenses stand up as ridges above the inclosing schist.

The schists making up the lower part of the Piracicaba formation are mainly argillaceous, gray, red, or purple in color. In the upper part sericitic, talcose, and quartzose schists are more common.

Next to the Caraça quartzite the Piracicaba formation is probably the most widespread of the metamorphosed sedimentary rocks. It is almost coextensive with the former, except in the northern part of the district where it is absent in many places on account of faulting, but on the other hand it is present in places where the Caraça quartzite is absent, as in the region southeast of Bello Horizonte.

Like the other sedimentary rocks, the Piracicaba formation is of variable thickness. Furthermore it is not always easy to draw the division line between this formation and the overlying Itacolumi quartzite, since beds of quartzite become increasingly prominent, in the upper portion of the Piracicaba formation. And as the Itacolumi quartzite is represented only at a comparatively few points in the district, the full thickness of the Piracicaba formation is to be observed only in a limited number of places. But judging from the exposures where the entire formation is present, it would seem to be seldom less than 300 meters in thickness and generally many times this. It is a great mass of sediment, of sufficient bulk to lay a heavy tax upon nearly any system of dynamics and method of sedimentation which may be supposed to have resulted in this thick pile of beds.

*Itacolumi quartzite.*—The series of indurated rock formations is capped, so far as the iron-ore district is concerned, by a thick quartzite which is not very different lithologically from the Caraça quartzite. As this upper formation is perhaps displayed to best advantage in the prominent peak of Itacolumi, the popular lookout point near Ouro Preto, it may well take its name from that well-known mountain. It is the youngest member of the regular sedimentary series yet discovered in central Minas.

While this formation where best exposed is predominantly quartzite, it contains also a large proportion of schistose rocks. The quartzite grades laterally into sericite, quartz, and talc schists, so that, in places, the formation is largely composed of schist with a few prominent and persistent layers of quartzite. This variation in lithology is so characteristic both of the Piracicaba formation and of the Itacolumi quartzite that the two may perhaps well be regarded as one formation, being formed during a continuous period of deposition, schists predominating in the lower part and quartzite in the upper part. They strongly suggest delta deposition, individual layers being seen to grade from coarse quartzite into argillaceous schist within a distance of 4 or 5 kilometers.

In fact, there is much to indicate delta deposition in most of the members of the Minas series. The Caraça quartzite, Itabira iron formation, Piracicaba formation, and Itacolumi quartzite all exhibit rapid lithological variations as their layers are traced along the strike as well as across it. At the same time, they show also in some places great thicknesses and extremely rapid variations in thickness. These are not the results to expect if the sediments were laid down in regular succession upon the relatively flat and uniform ocean floor; but they are just what might be anticipated if they represent the topset, foreset, and bottom-set beds of delta formation. Under the former hypothesis it is not easy to see how such great thicknesses of shallow water deposits could be formed under any rational system of crustal dynamics; under the hypothesis of inclined sedimentation the total thickness of the series of shingling layers laid down in shallow water may very easily become as great as the strata of the Minas series require.

The name Itacolumi is an old one in geological literature and has been variously applied by different writers. As far back as 1822 Eschwege proposed the name itacolumite for a quartzose talco-micaceous rock which he found abundant in, and characteristic of, the gold and diamond fields of the Serra do Espinhaço.[1] Eschwege himself recognized that the rocks to which he gave the name itacolumite were not a unit, and in consequence noted two groups, one schistose and the other massive, but he lumped together under the general name of itacolumite all the quartzose rocks of the region, which has been an incubus on Brazilian geological studies.[2]

For a long time these rocks were generally regarded as belonging to the primitive igneous crust of the earth,[3] but later geologists have shown them to be clearly metamorphosed sediments. By the more recent writers (Derby, Gorceix) the two divisions of the original itacolumite have been considered to be independent formations.[4]

While the term itacolumite has been variously applied to the quartzites and quartz schists of the Serra do Espinhaço, it also has been used as a petrographical term to designate the peculiar flexible sandstone, or quartzite, which is an oddity found at several points in the district.[5] But this property of flexibility is characteristic of only an insignificant portion of the whole formation.[6] If the term be retained for the future, its only proper place would seem to be as the petrographic name for this flexible phase of the quartzite, for there seems to be little reason for applying a single mineralogical or petrological term to such a great and varied succession of metamorphosed sedimentary formations as are now found to make up the Backbone Range.

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[1] Wilhelm von Eschwege, cited by O. A. Derby, "On the Accessory Elements of Itacolumite, and the Secondary Enlargement of Tourmaline," *Am. Jour. Sci.*, V (1898), pp. 187–92.

[2] O. A. Derby, "The Serra do Espinhaço, Brazil," *Jour. Geol.*, XIV (1906), footnote, pp. 374–75.

[3] A. de Lapparent, *Traite de Geologie*, 2d ed., 1885, p. 654.

[4] O. A. Derby, *Am. Jour. Sci.*, V (1898), 187.

[5] E. S. Dana, *Textbook of Mineralogy*, p. 190.

[6] O. A. Derby, "On the Flexibility of Itacolumite," *Am. Jour. Sci.*, 3d ser., XXVIII (1884), 203–5.

Itacolumite as a formation name has been used, not only for the quartzite above the iron formation (the quartzite out of which the peak of Itacolumi has been carved), but also for the great quartzite series (Caraça quartzite) which, throughout the district, underlies the iron formation. That the quartzite which makes up the peak of Itacolumi is distinct from the tremendous quartzite formation of the Serra do Caraça is a fact which does not seem to have been brought out clearly by those who have studied this region; nor has it been clearly recognized that the quartzite which forms such a large part of the Serra do Espinhaço from Ouro Preto northward to Diamantina is the lower. But these two quartzite formations are quite distinct and are separated from one another by the Itabira iron formation and two schist series. If the name of Itacolumi be applied to one of the quartzite formations, it would seem fitting that it should be applied to that one which occurs in the peak of Itacolumi. This is the upper quartzite.

In areal extent the Itacolumi quartzite is much more limited than the Caraça quartzite. This is chiefly the result of erosion which has swept away the upper members of the Minas series from many localities where the lower members still remain. The Itacolumi formation is nowhere better displayed than just south of the city of Ouro Preto in the mountain ridge which culminates in the peak of Itacolumi, where there are perhaps 1,200–1,500 meters of quartzite exposed. The upper quartzite appears again on the north limb of the Ouro Preto anticline, as a conspicuous ridge just north of the village of Bento Rodrigues.

Whether the Itacolumi quartzite was once overlain by younger sediments of the same general series, or not, is uncertain. As yet, no evidence of a younger member of the series has been recognized. But as the Itacolumi quartzite, though a resistant formation, remains only at a few points in the whole district, it is not impossible that younger, and less resistant, beds may once have capped it and since been removed by erosion.

*Summary.*—This whole great series of sedimentary formations is apparently conformable throughout. Above the base of the Caraça quartzite no unconformity of any moment has been noted. But from top to bottom, not a single fossil has been found within the series which might aid in determining its geologic horizon. The strata have been metamorphosed to such an extent that fossil forms might originally have been present in these beds and have since been obliterated in the process of metamorphism. But to what extent the absence of fossils is due to an original paucity of impressions in the original sediments, and to what extent to obliteration of existing forms by subsequent metamorphism we cannot say. The age of the series therefore remains problematic. It is simply known to rest unconformably upon the probable Archean complex. The general nature of the strata harmonizes well with the hypothesis that these beds are of pre-Cambrian age. This is the age generally assigned to the series by the geologists of the Brazilian Survey. At the present time we can hardly go farther than to note the general parallelism between this Brazilian metamorphic series and the Proterozoic sediments of other parts of the world, especially the Lake Superior Algonkian series. The heavy quartzites, schists, and iron formations indicate not very widely different conditions in these two regions. But while the sedimentary series in Minas presents a strange parallelism to the Algonkian series of the Lake Superior region in North America, and to various other pre-Cambrian terranes, no definite evidence has yet been found to preclude its belonging in whole, or in part, to the early Paleozoic.[1]

### PRE-DEVONIAN DEFORMATION

Just when this long period of sedimentation in central Minas was interrupted is not yet apparent. What is known is that it was followed, whether shortly, or after a considerable interval, by a period of great deformation. Mountain-making movements profoundly affected a belt running across central Minas.[2] The strata were both folded and thrust-faulted on an extensive scale. At the same time the rocks suffered metamorphic changes; the sandstones became quartzites, the shales were altered to the present schists, the carbonate rocks were recrystallized, and the iron formation dehydrated to the hematite and itabirite which we see today.

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[1] See J. C. Branner, *Geologia Elementar*, Rio de Janeiro, 1906, p. 217.

[2] O. A. Derby, "The Serro do Espinhaço, Brazil," *Jour. Geol.*, XIV (1906), 347-401.

The rocks did not everywhere yield to the stresses in the same way. In the southeastern part of the district the strata were thrown into open folds, though these folds show less symmetry than those of the Jura or the Appalachian system. With the folding there is also some faulting associated. But in the northeastern portion of the district very little folding has occurred. That region has suffered, instead, very extensive thrust faulting which repeats the sedimentary series, and by thus repeating the outcrops of iron formation becomes a factor of much economic importance. The fractures have occurred along lines trending for the most part northeast and southwest, or parallel to the Atlantic coast. The faults are overthrusts from the southeast and east.

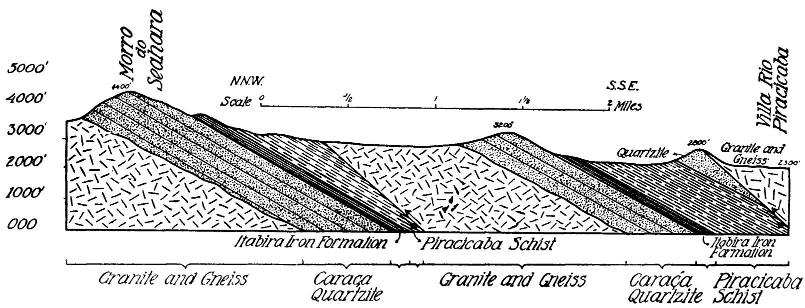

FIG. 7.—Slice-faulted section between Villa Rio Piracicaba and Morro do Seahara

The type of faulting can perhaps best be described as slice faulting (Fig. 7). The strata, instead of yielding to the stresses by wrinkling and folding, were sliced off in a succession of inclined blocks nearly all dipping toward the east or southeast, and the crustal shortening accomplished by movements between the inclined slices. In the northern portion of the Minas Geraes iron-ore district, the slice faulting has caused an alternation of the crystalline complex with the sedimentary series. Nearly everywhere the basement complex is the surface formation on the upthrust side. On account of the great erosion which the region has suffered since the period of deformation, the sedimentary formations have persisted only on the downthrown side of each fault. In the western part of the district also, faulting would seem to dominate folding.

Some of these fault lines are apparently of great length. A great fault forms the eastern front of the Serra do Espinhaço, or Backbone Ridge, at Cocaes and from there runs northward for many miles. Then, as we go farther north, there appear in front of it to the east successively new faults arranged *en échelon*. Each of these, in turn, commences a new front range slightly to the east of the previous range. The old ranges continue northward as successive ridges behind the front. This system of faulted ranges runs northward into the state of Bahia.[1] The displacement along the major fault planes cannot be determined, inasmuch as the sedimentary formations have completely disappeared from the upthrust side, so that the crystalline complex alone remains. It is probably great. In the minor slice faults the displacement in some cases is as low as 300 meters. In general the faulting in central Minas Geraes shows a marked similarity to that in the Appalachian region of the United States and that in the Canadian Rockies of Alberta.

These deformative movements were very general, apparently involving most of the Atlantic border of Brazil south of Cape St. Roque, and possibly also Uruguay and portions of the province of Buenos Aires in Argentina. The mountains formed at this time would seem, in a way, to be the Atlantic counterpart of the Andean ranges on the Pacific border. South America was squeezed from the Atlantic first and from the Pacific later.

How closely the period of deformation followed the sedimentation is as yet unknown. Minas Geraes affords little evidence, but in several of the neighboring states, Matto Grosso, São Paulo, and Parana, strata of Devonian age, but slightly disturbed, are found resting unconformably upon the wrinkled strata which participated in these orographic movements.[2] The mountain-building movements were therefore accomplished before the Devonian. That the deformation did not immediately precede the Devonian is evident from the amount of erosion suffered by the mountains before the incursion of the early Devonian sea. In São Paulo and Parana, the basal beds of the Devonian (which have been assigned to Lower Devonian) rest unconformably on a westward dipping, now slightly warped surface of these old deformed rocks in such a manner as to show that the sea crept in over a region of little or no relief.[1] An interval of much erosion is therefore implied.

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[1] O. A. Derby, *op. cit.*

[2] J. E. Branner, *Geologia Elementar*, pp. 230–31; O. A. Derby, "Geologia da região diamantifera da Provincia do Parana, no Brazil," *Archivos do Museu Naçional de Rio de Janeiro*, III (1878), 89–96.

The location and trend of these mountain ranges is worthy of note for their bearing upon the major problem of earth movements and deformation. It is no new fact that the ranges of eastern Brazil are rather strikingly parallel to the border of the continent, and not far back from the coast. In Minas Geraes the repeated overthrust faulting has nearly all come from the southeast. The strata of the faulted slices nearly always dip toward the Atlantic. The picture of the Atlantic Ocean segment crowding the eastern side of the South American continent, squeezing it and forcing it upward like a triangular wedge and wrinkling and slicing the edge comes very appealingly to mind. At a later time the Pacific Ocean segment seems to have done the same on that side.

### PALEOZOIC—EARLY MESOZOIC EROSION PERIOD

After the great period of mountain-building we have evidence only of a long period of erosion whose final result was to develop an approximate base-level which is, at present, only preserved on the crest of the Serra do Espinhaço. The amount of material removed from the upthrust blocks was great, suggesting that the interval between the end of the deformation and the completion of the base-level was a long one. The process of base-leveling was probably not rapid, since the hard Caraça quartzite is a very resistant formation and would have been reduced slowly. That the process progressed nearly to completion is evidenced by the character of the crest of the Serra do Caraça which, even today, preserves in places a well-developed plain (Fig. 8). The Serra do Caraça being composed of more resistant rock than the surrounding region, this quartzite area would be the last portion of the region to be brought to base-level. As the upturned Caraça strata were truncated, it is safe to assume that all the rest of the region was close to base-level.

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[1] J. B. Woodworth, "Geological Expedition to Brazil and Chile, 1908–9," *Bull. Mus. of Compar. Zool. Harvard College*, LVI, 42.

### MESOZOIC—EARLY TERTIARY DEPOSITION

*Diamantina conglomerate.*—On the truncated, even crest of the Serra do Espinhaço, high-level gravels, now cemented into a conglomerate, are found at various points along the range, particularly in the vicinity of Diamantina. The top of the Backbone Range in that region is very broad, partaking perhaps rather more of the nature of a narrow plateau belt than of a mountain range. The broad open tracts of comparatively level upland are so distinctive as to have been termed *chapadas* (table-lands) by the natives. While considerably dissected by subsequent erosion, the broad open country upon the top of the Backbone Range is the modified surface of the old peneplain (Fig. 9). At various points on these *chapadas*, or upland plains, especially in hollows or former river

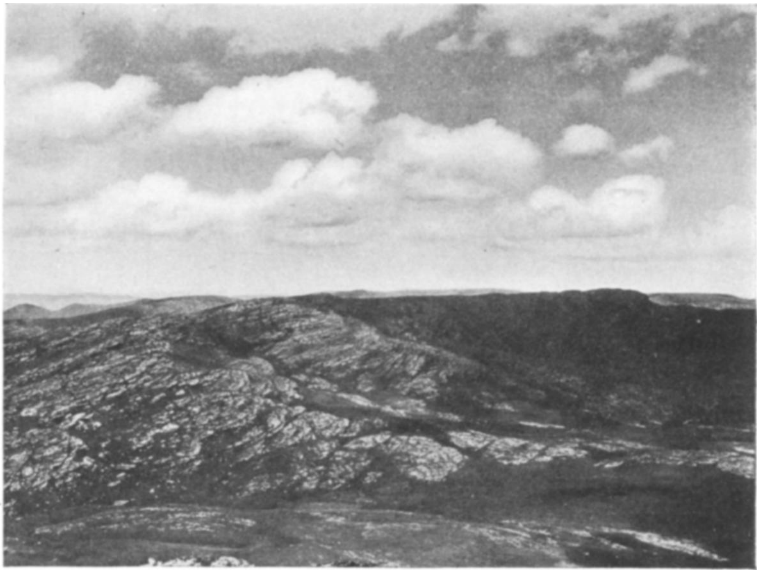

FIG. 8.—Peneplained crest of the Serra do Caraça, near Alegria. The inclined quartzite strata have been trunkated and the old erosion surface still persists over extensive areas on the top of the Backbone Range.

channels in the old surface, are found deposits of residual clay and gravel, more or less imperfectly cemented. This material is all thoroughly weathered and of a residual nature. The pebbles in the conglomerate are mostly of quartzite, but with a sprinkling of pebbles of iron formation, schist, quartz, basic igneous rock, and diamonds. With the conglomerate is associated a considerable amount of sand and of clean white to pinkish clay, mostly kaolin, with some bauxite. This material for the most part represents the final products of the rock weathering, and its presence perched upon the smooth crest of the Serra do Espinhaço above the rest of the region would suggest that it is to be connected with the base-level stage in the history of the region. This is the celebrated diamond-bearing conglomerate which has brought fame and wealth to the district, and which would be interpreted in physiographic studies as the high-level gravels which mark the peneplain stage. Subsequently, during later erosion cycles, some of the conglomerate

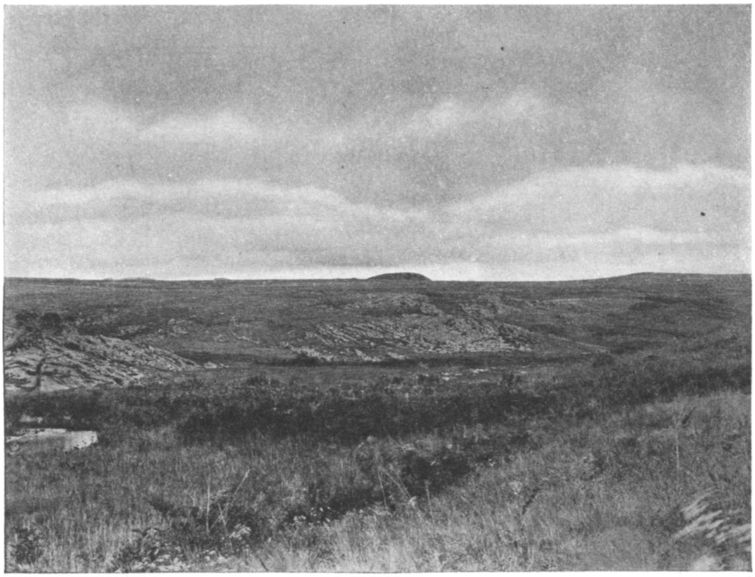

FIG. 9.—A *chapada*, or tablè-land, forming the summit of the Backbone Range near Diamantina. The diamond-bearing conglomerates are accumulations of residual gravels collected in depressions or old stream channels on the peneplained surface.

material has been washed down on to lower benches and terraces along the courses of some of the streams which dissect the plateau, and today diamond mining operations are also carried on at these lower levels.

### LATER EROSION AND DEPOSITION PERIODS

*General uplift.*—As to the age of the peneplain nothing definite is known, but it would seem most likely to belong to the late Mesozoic or early Tertiary. At some time subsequent to the formation of the plain, the region was uplifted as a whole with but little change in the attitude of the strata. Rejuvenated erosion then commenced to carve the present mountains out of the uplifted plateau. The resistant quartzites remained as ridges, while the softer schists and readily disintegrated granites and gneisses were more rapidly worn down and removed. In this tropical country the granites and gneisses appear to be the least durable of the formations, owing to the rapidity with which they crumble to pieces following the weathering of their ferromagnesian constituents. The micas, amphiboles, and pyroxenes are readily attacked by humic acids and by the carbon dioxide of the atmosphere. Weathering of these constituents allows the crystalline mass to crumble into arkose which is removed by the streams. The result is that in Minas Geraes the areas of granite, because of the feeble resistance of this kind of rock to the accelerated chemical action characteristic of weathering in the tropics, have become the lowlands. Some prominent granite ridges occur, but on examination it is generally found that they are composed of light-colored granite in which the ferromagnesian constituents play a subordinate part. The quartzite formations in general owe their resistance to erosion mainly to the fact that they contain a very small percentage of readily decomposable minerals.

*Tertiary canga plains.*—The erosive processes which have carved the mountains of central Minas Geraes from the uplifted peneplain did not go on uninterruptedly. There were times of checked erosion, locally at least, followed by rejuvenation. These lesser cycles are shown by various local plains and remnants of plains in different parts of the region. One of the most notable of these is the high-level canga plain in the locality known as Gandarella, 40 kilometers northwest of Ouro Preto.

Canga (from Itapanhoacanga, a village in central Minas) is a peculiar ferruginous conglomerate consisting chiefly of fragments of iron formation cemented with a nearly pure iron-oxide cement. It is formed by a surface disintegration of the iron formation which consists largely in the removal of silica, and solution and redeposition of iron oxide. In some places the canga has been deposited almost *in situ*, while elsewhere it has been transported for considerable distances and deposited, either on areas of iron formation, or on adjacent areas of other rocks.

Such canga deposits have probably been forming ever since the iron-formation beds were exposed to surface erosion, and are being abundantly formed at the present time. As a consequence they are found at many different elevations. A long period of quiescence, like that in which the land was worn low following the pre-Devonian deformation, was therefore probably accompanied by abundant canga deposition which formed extensive canga plains on, and adjacent to, the belts of iron formation. But subsequent erosion has been so extensive that today few remnants of canga formed during the great base-leveling period remain.

The Gandarella canga plateau, already mentioned, is the most conspicuous of the high-level canga plains and is situated on the summit of the divide separating the waters of the upper Santa Barbara valley from those of the upper valley of the Rio das Velhas. This canga plateau has an approximate elevation of 1,450 meters, a little lower than the Serra do Caraça. Whether it is to be regarded as a portion of the Caraça peneplain, now at a lower level than the rest of the plain, and so more or less contemporaneous with the Diamantina conglomerate, or whether it is to be taken as the work of a later cycle of erosion, and to be correlated with evidences of planation at a similar elevation in Alegria and near Antonio Pereira, may perhaps best be left open for the present. Deep valleys have been cut in this remnant of the canga plateau along both sides of the divide. Along the bottom of one or two of these at Gandarella, there occur irregular deposits of clay and sand containing lignite and fossil leaves. On the basis of the plant remains, these deposits have been referred to the middle or late Tertiary—probably Miocene or Pliocene.[1] They are distinctly younger than the canga plateau which is therefore certainly older than the Pliocene, and probably older than the Miocene.

Similar deposits of Miocene or Pliocene clay, sand, and lignite occur near the village of Fonseca,[2] east of an extensive canga plain of later age, which occurs along the eastern front of the Serra do Caraça. This younger plain is very conspicuous over the areas of softer formations east of the Serra do Caraça. The canga plain abutting the east foot of the Serra do Caraça between the village of Agua Quente and Santa Rita Durão (Fig. 10) is a particularly well-preserved portion of it. The softer schists, gneisses, and granites east of the present Serra do Caraça had, with the exception of some of the more resistant lenses in the iron formation, been

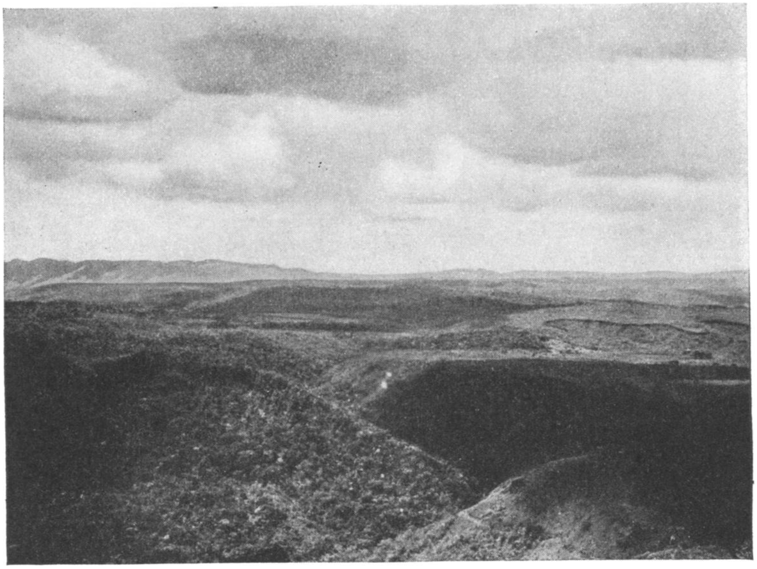

FIG. 10.—A plain of canga formation, between Santa Rita Durão and Agua Quente.

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[1] H. Gorceix, "Bacias terciarias de agua doce nos arredores de Ouro Preto," *Ann. da Escola de Minas de Ouro Preto*, III, 95–114; Rio de Janeiro, 1884; Joaquim Candido da Costa Sena, *Ann. da Escola de Minas*, N. 10 (1908), p. 17.

[2] H. Gorceix, *op. cit.*

reduced to a common level. Upon this plain, material washed down from the iron-formation monadnocks developed a covering sheet of canga. The canga formation, by obliterating some of the remaining irregularities in the erosion surface, has produced a remarkably level plain, much of which still remains. This canga plain is now at an average altitude of about 900 meters above the sea. Judging from the occurrences at Fonseca it appears to be of later age than the lignite deposits, which have been referred to the Miocene or Pliocene, and would seem to belong to the late Tertiary. Over considerable areas it has scarcely been trenched at all.

*Conglomerate formations.*—Benches, and other remnants, corresponding to the canga plains in the neighborhood of the iron formation, are also to be seen in the Diamantina region. These remnants occur in the neighborhood of the streams which have worked back and partially dissected the plateau-like Backbone Range. As the formation of the range is quartzite, the gravels developed on these plains are quartzose, though possibly to be correlated with the iron-formation conglomerate, or canga, of the iron-ore district. As these gravels and conglomerates are composed of concentrated residual material derived from diamond-bearing formations, they have been extensively worked for diamonds.

### PRESENT STATUS OF EROSION

The formation of these several Tertiary plains was terminated supposedly by uplifts which accelerated stream action and started their dissection. Portions of the canga plain near Agua Quente have suffered considerable erosion since its formation. Toward the northeast, in the region between the Serra do Caraça and the Piracicaba iron-ore district, the plain has been much carved. This area being for the most part farther from the hills of iron formation, the thick capping of tough canga which has preserved the plain intact at Santa Rita Durão and Agua Quente was much less developed. As a result, erosion progressed more readily. The easily weathered underlying granites and gneisses which almost exclusively make up this region have been cut into a state of mature erosion, though the level of the former peneplain is well preserved in the tops of these low hills.

As no attempt was made to correlate erosion cycles in the different parts of the district, little can be said of these upward movements of the land surface. One such uplift of the plateau-forming type which affected the coastal region of Brazil in this latitude was that which has given rise to the Serra do Mar, or Coast Range. The effects of this movement were undoubtedly felt by the drainage systems farther inland in Minas Geraes. The Serra do Mar presents a very abrupt face toward the sea. At many points it is really a plateau scarp which has the appearance of a mountain range when viewed from the coast. Judging from the abruptness of this plateau scarp, the upward movement which produced it must have occurred late in the Tertiary, or possibly even early in the Pleistocene.

*Present topography.*—The present topography of central Minas Geraes has resulted, to a very large extent, from differential erosion of rock formations which offer varying resistance to the processes of degradation. The mountains and ridges, valleys and plains, have been carved out of a region which has been folded and faulted and afterward reduced to base-level. The location of the present topographic features has been determined by the underlying rock structure. Wherever, because of faulting or folding, the heavy quartzite formations appeared at the surface of the plain out of which the present topography was sculptured, they resisted erosion far more than the other rocks, and now remain as mountain ridges. The iron formation, at most points somewhat less resistant than the quartzite, but throughout most of its extent more lasting than adjacent schists, stands up as a chain of foothills in approximately parallel arrangement to the higher quartzite ridges. The schists, by yielding more readily to erosion, have developed comparative lowlands in the midst of which isolated ridges appear wherever a lens of quartzite, or hard iron formation, occurs.

But the conspicuously weak formation is the basement complex. The granites and gneisses are especially susceptible to the chemical disintegration which is induced by the tropical conditions. Their ferromagnesian constituents are so readily attacked by the carbon dioxide of the atmosphere and the humic acids from the rank vegetation, aided by the hot, humid climate, that the rock rapidly crumbles to pieces and the crystalline areas become lowlands. But on account of comparatively recent uplifts, the granite areas of central Minas Geraes are not yet reduced to plain conditions, though they represent a state of advanced erosion. The hills are mostly small and very numerous. They produce the peculiar knobby, hummocky topography which characterizes so many areas of crystalline rock within the tropics, and which has been aptly likened by Eschwege to the billows of a rolling sea (Fig. 11). Wherever erosion has become sluggish in these lowland areas, the rapid disintegration of the crystalline rock has formed a very thick covering of mantle rock which effectively conceals the solid rock from view.

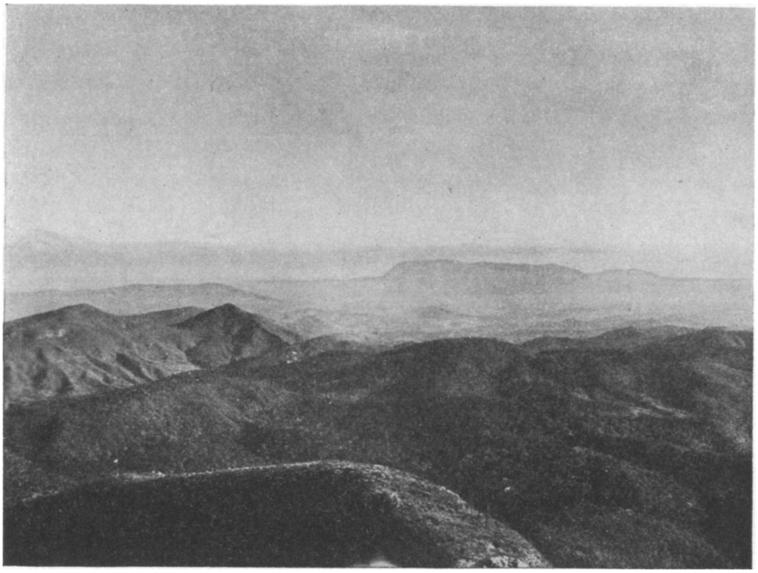

FIG. 11.—View toward the Serra do Caraça from the Morro do Seahara showing the topography resulting from the unequal resistance of the formations; quartzite ranges in the foreground and in the distance; Morro Agudo, a pyramidal peak of iron ore, to the left of the center of the picture, and the billowy lowlands of granite beyond.